

Economic, environmental and health co-benefits of the use of advanced control strategies for lighting in buildings of Mexico

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ABSTRACT

Merida, Mexico, is a city that spends 17% of its electricity for lighting purposes. This electricity comes from thermal power plants that use fossil fuels. These emit a large amount of particulate matter, around 2.5 micrometers (PM_{2.5}), which can penetrate deepest lung parts (alveoli), causing cardiovascular disease. Mexico has a policy (NOM-028-ENER-2010) that establishes the minimum efficiency for lighting in buildings. However, lighting is often used inappropriately (e.g. daytime or when there are no people using them). One solution for this problem is to use control device technology of multiple types (combination of daylight, motion and presence sensors). However, these strategies have not been fully implemented in Mexico, mainly due to the high cost of commercial control devices. This study aims to know the lost co-benefits when control devices are not implemented for lighting cost reduction, such as: energy saving (kw-h/yr), electricity bill reduction (USD/yr), PM_{2.5} emission reduction (µg/m³), cardiovascular death reduction (death/yr) and cardiovascular death cost reduction (USD/yr). For those reasons, it is recommended that energy policy decisions regarding building lighting efficiency include the implementation of control devices. Moreover, such policies should be preceded by research studies focused on detailed device cost, co-benefits and socio-economic analysis.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) is an association for the assessment of climate changes and its potential environmental and socio-economic impacts. Its annual Climate Change Report has mentioned changes in average temperature of the Earth, desertification, land degradation, sustainable land management, food security, sea level, and greenhouse emission. These changes are due mainly to anthropogenic pollutants, especially Climate Altering Pollutants (CAPs) (Pachauri et al., 2014). This happens when the pollutants emitted by anthropogenic activities exceed the absorption, assimilation, or adaptation capacity of ecosystem elements (Hydrosphere, Lithosphere, Biosphere, Atmosphere and Sociosphere), since interrelations and interactions exist between them (Wall and Gong, 2001; Gong and Wall, 2001; Diaz-Mendez et al., 2011, 2013). Evidence of these can be found in prestigious literature. Vallero reported that air pollutants can damage both ecosystem function and ecosystem structure, including biodiversity. Furthermore, the author evidenced damage in coral reefs and rain forests due to acid rain (Vallero, 2014). Snakin et al. explained variations of soil carbonate concentration and how these

changes can increase carbon dioxides concentration in the atmosphere (Snakin et al., 2001). Xiaomin et al. studied the impacts of the changes of nitrogen deposition in soil, which affects nitrogen cycle in forest ecosystems; these changes are due to the nitrous oxides that come from burning fossil fuels (Zhu et al., 2015).

Also, Sociosphere is affected by pollutant emissions, such as CO, NO_x, SO_x, PM₁₀, PM_{2.5}, VOCs and others (Woodward et al., 2014). Air pollution comes from different sources, such as power plants used to generate electric power, oil production plants (offshore, inshore, and refineries), cars, and others (Diaz-Mendez et al., 2012). All of them contribute to chronic effects on human health such as respiratory, heart, lung and cancer diseases. Moreover, they can aggravate pre-existing conditions, such as asthma and cardiovascular diseases (Perez et al., 2010; Brook, 2008), increasing the rate of mortality in a population (Dockery et al., 1993; Kampa and Castanas, 2008).

However, problems related to pollutant emissions will most likely continue due to the strong dependence of the society on fossil fuels (Kampa and Castanas, 2008). The International Energy Agency (IEA) reported that primary energy source in countries of the Organization for Economic Co-operation and Development (OECD) are as follows: oil,

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Nomenclature

Br	breathing rate of a person ($\text{m}^3/\text{day-person}$)
C	percentage of electrical energy consumption increased or decreased
CD	mortality rate of cardiovascular death per year over 100,000 (person/year)
ΔC	change in exposure concentration of a pollutant over the population ($\mu\text{g}/\text{m}^3$)
ΔCD	change of cardiovascular death per year (death/year)
E	annual electrical energy consumed per residential building (MW-h/yr)
EF	emission factor of a specific pollutant from the power plant (kg/MW-h)
ΔEE	change of total annual electrical energy consumption (MW-h/yr)
ΔE	change of emission of a specific pollutant ($\mu\text{g}/\text{day}$)
F	percentage of the annual electrical energy used in

	lightings
iF	intake fraction
N	number of residential buildings that have electrical energy supply
P	population

Subscript

building	residential building
lighting	lighting
NOx	nitrous oxide
PM _{2.5}	particulate matter less than 2.5 μm
PM _{2.5} by NOx	formation of PM _{2.5} from nitrous oxide
PM _{2.5} by SOx	formation of PM _{2.5} from sulfur oxide
total PM _{2.5}	total formation of PM _{2.5}
rate	related to cardiovascular death per year over 100,000
SOx	sulfur oxide

31.2%; coal, 29.4%; natural gas, 21.2%; renewable, 13.4%; and nuclear, 4.3% (IEA and Energy Balances of OCDE Countries, 2015). Consequently, 82% of the primary energy sources in the world come from fossil fuels. Moreover, the report has mentioned that the consumption of primary energy sources by sector are divided as follows: transport 33%; industry, 31%; residential, 20%; services, 13%; and others, 3%, including agriculture, forestry, fishing and non-specified (IEA and Energy Balances of OCDE Countries, 2015). Thus, the primary energy sources in the present and in the immediate future are the fossil fuels.

OECD countries use one part of their primary energy sources to generate electric power. Most of the electricity is produced in power plants, and around 59% of these plants use fossil fuels. The additional 41% of electricity is produced from other sources, such as nuclear, 19%; hydro, 13%; and others, 9% (geothermal, solar, wind, tide, biofuels, waste and heat) (IEA and Energy Balances of OCDE Countries, 2015). Most of the electricity is used in the industrial, residential, commercial, and public service sectors. This represents around 93% of the total electricity consumption in the world (IEA and Electricity Information, 2015).

Mexico has the same world trend in energy uses. The last energy balance mentioned the primary energy sources used in Mexico are divided as follows: fossil fuels, 88.09%; renewable, 7.5%; coal, 3.51%; and nuclear, 1.36%. Consequently, fossil fuels are the main primary energy source in Mexico (SENER, 2013). Moreover, the same report presents the final consumption of primary energy sources by sector as follows: transport, 44.1%; industry, 31.4%; residential, 17.7%; agriculture, 3.1%; and others, 3.7% (SENER, 2013).

One part of this primary energy sources is used to produce electricity: fossil fuels, 72.4%; hydro, 21.9%; nuclear, 3%; and renewable, 2.7% (geothermal, solar, and wind) (SENER, 2014). The fossil fuels used in electric power generation are: natural gas 83.4%; oil, 13.0%; diesel, 0.9%; and coal, 2.8% (SENER, 2014). The consumption of electricity by sector is: industrial, 62.7%; residential, 32.4%; agriculture, 4.4%; and transport, 0.5% (SENER, 2014). Nearly 95% of the total electric power produced in Mexico is consumed in industrial and residential activities, mainly buildings.

Mexico has a vast resource of fossil fuels, being the fifth larger fossil fuel producer in the world, which strengthen its dependency on them. On the other hand, Mexico has significant environmental and social problems that arise from the large amount of pollutant emitted from power plants to generate electricity. These pollutants are mainly emissions of SOx from combustion of fossil fuels with high-sulfur contents (López et al., 2005), and PM_{2.5} emitted from combustion of heavy fuels (Herrera Murillo et al., 2012). Environmental and health concerns

related to air pollution also depends on weather conditions of the power plant location (Mugica et al., 2009).

A solution for those environmental and health concerns in Mexico due to pollutant emission could be the use of renewable energy sources. Mexico has a large solar and wind energy potential (Hernández-Escobedo et al., 2015, 2010). However, only 7.5% of the primary energy sources comes from renewable resources (SENER, 2013). Only 2.7% of the electric power generated in Mexico comes from renewable sources (SENER, 2014). Furthermore, for industrial and residential owners in Mexico the total cost of solar or wind energy technologies are still more expensive than conventional generation. In consequence, high costs of solar and wind energy technologies, and the socio-economical aspects of Mexico are the main obstacles to implement alternative energy conversion in Mexican buildings.

As mentioned by Woodward, energy improvement using efficient technology and policy could mitigate pollutant emissions (Woodward et al., 2014). Energy control strategies represent another solution to reduce pollutant emissions that arise from electricity consumption in buildings, focusing on equipment with large power consumption, such as cooling, heating (Diaz-Mendez et al., 2014; Diaz et al., 2013), and lighting (Van De Meughevel et al., 2014). Lighting is the second major power consuming application in Mexican buildings. Due to Mexican diverse climate conditions, there are buildings where air conditioning is indispensable, representing around 51–77% of the total electric bill, while lighting does around 8–17%. Lighting represents around 35% of the electrical bill in buildings where air conditioning is not indispensable (CONUEE, 2015). The average electric energy used for lighting in Mexican buildings is around 2200 kW-h/yr (CONUEE, 2015). For these reasons, lighting is the focus of study in this work.

Economic, environmental, and health co-benefits energy consumption reduction could be reached using lighting control devices, bringing economic, environmental, and health co-benefits. However, these strategies are not fully implemented in Mexican buildings, since commercial control devices are too expensive. Furthermore, reduction of electrical energy usage from lighting could help to reduce pollutant emissions from thermal power plants that use fossil fuels, thus bringing global and local climate benefits (Argyriou et al., 2012). These can be specially extended as health benefits to the population living in the surroundings of those power plant (Woodward et al., 2014).

A solution to reduce energy consumption for lighting in buildings could be the use of control strategies (Abdelaziz et al., 2011). As mentioned by Aghemo et al. Aghemo et al. (2014) that carried out a study to evaluate the energy efficiency of a control system for lighting in buildings, the results obtained indicates the importance of a correct design or implementation of control strategies, the authors suggested

that control strategies can reach potential of electrical energy saving between 17–32%. Also, there are different research studies reporting on the problems of lighting in buildings, aiming to reduce electricity consumption using control, dimming or other devices. Most of them have approaches on mathematical modelling, simulations, experimentation, methodologies, and recommendations (Doulos et al., 2008; Li et al., 2014). For instance, Lo Verso et al. (2014) reported on the implementation of control strategies modelling and correlation to predict lighting energy consumption in buildings. They presented two high performance mathematical models to predict the electricity used in building lighting. One model considers a manual ON/OFF control, and the second one considers an automatic control system that assesses the presence of natural light. These models were produced from data obtained through 828 cases simulated in the program Daysim. Thus, the authors quantified the mean squared error (MSE) or mean squared deviation (MSD) at 0.66% for the manual control system and 0.29% for the automatic control system. According to the authors, these data should be further analyzed to obtain a more accurate and fast prediction of the energy used in buildings for lighting purposes. Additionally, Soori and Vishwas (2013) used Daysim, to propose a lighting control strategy for efficient use of the electricity in an office building. Furthermore, the authors also evaluated the impact of natural light and artificial light on the thermal load of the air conditioning systems to improve occupancy comfort. The authors proposed a lighting control strategy algorithm to achieve energy saving in buildings. The algorithm was evaluated using the commercial program Daysim, which yielded an optimum usage of lighting system. The use of the control strategy designed for the lighting system does not necessarily imply complexity, as reported by Wojnicki et al. (2014). The authors analyzed the complexity of designing and controlling lighting systems in buildings to reduce electrical energy consumption. As a result, the authors unveiled that control system design for lighting in a particular building can be very simple, and it has the possibility to be adapted for other buildings. Simple control strategies can generally aim to reduce electrical energy consumption in lighting system, as reported by Fernandes et al. (2014). The authors monitored the performance of dimmers to control a lighting system in the New York Times building. The dimmers had already been operating in the same building for a period of four years. During this time, it was observed that this equipment complied effectively with the reduction of electric energy consumption. The result obtained was 21 kW-h/m² of electrical power saved in lighting every year. This represents around 28% of the total energy used for lighting in the building.

The best lighting control device is a combination of lighting control strategies such as: occupancy (lighting usage according to the presence of occupants), daylighting (lighting in response to absence of natural light), personal tuning (adjusting individual lighting levels), and institutional tuning (adjustment of lighting levels to meet location specific needs or building policy). The two most common control strategies are: a) occupancy and personal tuning, and b) daylighting and occupancy.

Although there are commercial control devices for lighting, the Mexican market imports them. The cost of each control device ranges between 80 USD to 300 USD. A self-constructed control device for lighting was made for the present study, with an approximate cost of 8 USD and the same efficiency of the commercial ones. The objective is to know the lost co-benefits when control devices are not used for lighting: energy saving (kW-h/yr), electric bill reduction (USD/yr), PM_{2.5} emission reduction (µg/m³), cardiovascular death reduction (death/yr), and cardiovascular death cost reduction (USD/yr). Additionally, recommendations for future energy policy decisions regarding buildings lighting efficiency are made, which must include the implementation of control devices, but should be preceded by a device cost, co-benefits, and socio-economic analysis, to achieve its implementation. The methodology is applied to Merida.

2. Energy economics, environmental and health co-benefits analysis

The methodology used in this work estimates the benefits experienced when electricity consumption is reduced by using advanced control devices for lighting in buildings:

- First, energy and price analysis is made for commercial and a self-constructed control devices to estimate the energy saved in buildings:
 - A self-constructed control device is made; which includes daylight, motion and presence sensors. Also, commercial control devices were used.
 - The energy consumed by lighting with 64 T-8 lamps was measured with and without control devices (kW-h/yr).
 - The percentage of electricity reduction was estimated (%).
 - The amount of electric energy used for lighting in all buildings in Merida is estimated with and without control devices (MW-h/yr).
 - Price and socio-economic analysis is made.
- Second, estimation of environmental and health effects reduction:
 - Emission factors of the nearest power plant to the population of Merida were obtained (kg/MW-h of PM_{2.5}, SO_x, and NO_x). These emission factors depend on: a) the technology used by the thermal power plant (internal combustion, gas, or steam turbine, combined-cycle, etc.); b) the fossil fuel used in the power plant to generate electricity (diesel, oil, coal, gas, etc.); and c) weather conditions where the plant is located (Nazari et al., 2010). The power plant under study has data base of annual emissions (Sanchez, 2015). This amount is multiplied by the amount of energy consumption reduction to estimate the emissions reduction (µg/day).
 - A tool for air quality management called intake fraction is used. It is defined as the fraction of pollutant emission or its precursor that is inhaled by the population. This can be applied as a correlation to estimate the exposure concentration variation in the population's surrounding air (µg/m³) (Diaz-Mendez et al., 2012). In this study, special attention is focused on PM_{2.5} pollutants.
 - A toxicological examination is made to estimate the reduction of cardiovascular death per year linked to the reduction of pollution emissions (Diaz-Mendez et al., 2012).
 - The last step takes estimated the cost related to those avoided cardiovascular death per year.

3. Price analysis of advanced control devices for lighting in buildings

The most common types of control devices are daylight sensor (LDR) and motion sensor (PIR). An LDR control device turns on lighting systems in response to absence of natural light. However, if the room is unoccupied, the electricity is wasted. A PIR control device turns on lights according to the presence of occupants, but if the sensor is working during daylight, it turns on the lights, resulting in wasted electricity. Another problem with PIR sensors is the motion of the occupants. If they are inactive or passive after certain period, the sensor turns off the lights. However, there are commercial control devices that combine LDR and PIR with Ultrasonic sensors. The last one is used to detect if the person is still in the room. The cost of these devices can increase proportionally to energy consumption and room size, or if extra accessories such as AC to DC voltage converters are needed. Considering 2016 prices, the cheapest commercial control device with LDR, PIR and Ultrasonic sensors costs around 70 USD.

The implementation of this technology in residential buildings is not economically feasible, due to the financial constraints of the Mexican population. However, the adaptation of this technology might yield to cost reduction and their implementation in countries with persons living in poverty. To verify this hypothesis a self-constructed control

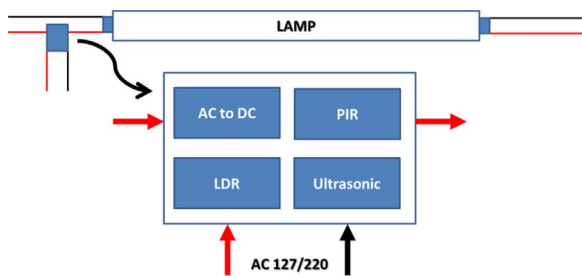


Fig. 1. Schematic of the self-constructed sensor.

Table 1
Energy and social economic results.

	Cost (USD)	Energy	Reduction	Labor days
Self-constructed	\$ 10.00	1339	35%	2.625
Commercial	\$ 70.00	1257	40%	18.375

device was made. The total cost of the sensor is as follows: LDR sensor, 1.0 USD; PIR Sensor, 1.0 USD; Ultrasonic sensor, 1.0 USD; Capacitive AC to DC converter components, 1.0 USD; CPU components, 6.0 USD; resulting in a total cost of 10.0 USD. Prices of self-constructed control device can be even lower if it is manufactured at an industrial level.

4. Self-constructed and commercial control devices electricity consumption reduction

A test was performed to compare the functionality of self-constructed control device versus commercial ones. Both controls with







LDR, PIR and Ultrasonic sensors. A schematic is illustrated in Fig. 1. Then, measurements are made in a room of a building with 64 T-8 lamps. Their datasheet indicates a power consumption of 32 W per lamp, bringing the overall power consumption to 2048 W, if all lamps are on at the same time. All T-8 lamps have only one switch to control lighting. A data logger was used to register voltage, electrical current and power consumption by the lighting system during 22 days for each control system. An average of 17 h of operation per day was observed during that period. A total energy demand of 778 kW-h was measured when no control devices are used. When control devices with LDR, PIR and Ultrasonic sensors were used, the energy demand was reduced to 505 kW-h with self-constructed control and 469 W with commercial control. Reducing the power consumption from 35% (self-constructed) to 40% (commercial). This reduction averages approximately 38% reduction in energy demand, using either systems. Commercial control exhibits superior performance due to its finer sensitivity, compared to the self-constructed one.

Table 1 illustrates the main analyzed parameters for self-constructed and commercial control devices, such as: costs, electrical measurements, percentages of reduction of electricity consumption, and the last column presents labor days needed for a person in Mexico to buy a control device.

4.1. Sensor operation

Table 2 illustrates the symbols corresponding to each state in which the control device can operate. When natural light is used in the room, the LDR sensor will remain off, and the sensing cycle will re-start. Consequently, the PIR and ultrasonic sensors will also remain inactive, keeping the electric lighting system off, as illustrated in Fig. 2(a). When there is not natural light, the LDR sensor will remain on and, if there is

Table 2
List of symbols and operation status of the control device for the electric lighting system.

Lighting system	
Symbol	Status
	On
	Off
Control device	
	Control device representation
	On
	Off
	On hold

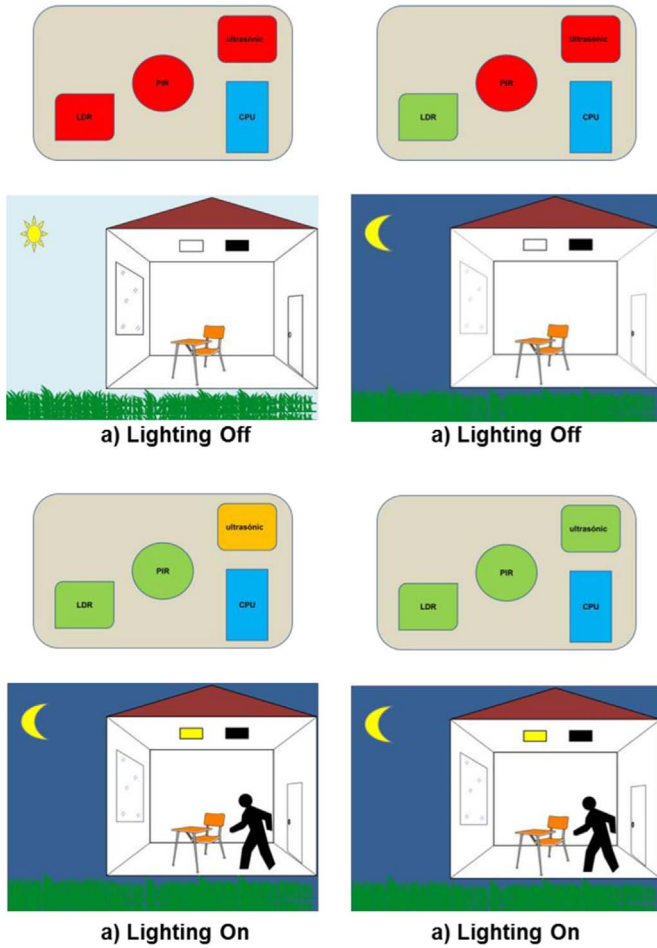


Fig. 2. LDR, PIR, and ultrasonic sensor operation.

not movement, the PIR sensor will remain off; therefore, the electric lights will be off Fig. 2(b), else if there is movement, the PIR sensor will also remain on; therefore, the electric lights will be on Fig. 2(c). Afterwards, there will be a signal delay that will indicate the presence of room occupants with the ultrasonic sensor, this will remain on hold if the signal delay is still active, keeping the lighting system on, and the cycle will re-start automatically Fig. 2(d). Finally, if there is not natural light, the LDR sensor will remain on, but in the absence of presence and movement, the PIR and ultrasonic sensors will remain off, consequently keeping the lighting system off, Fig. 2(b).

5. Co-benefit of the use of advanced controls devices in Merida

Merida has a combined-cycle power plant close to the population, which produces 988,256 MW-h/year.

Table 3
Data used for the city of Merida in Mexico.

Number of residential buildings that have electrical energy supply	489,688	(Aghemo et al., 2014)
Average total annual electrical energy consumed per residential building (kW-h/yr)	2200	(Hernández-Escobedo et al., 2010)
Percentage of electrical energy used in artificial lighting systems (%)	17	(Hernández-Escobedo et al., 2010)
Emission factor for pm2.5 (kg/MW-h) from power plant	0.655	(Abdelaziz et al., 2011)
Emission factor for SOx (kg/MW-h) from power plant	20.631	(Abdelaziz et al., 2011)
Emission factor for NOx (kg/MW-h) from power plant	1.633	(Abdelaziz et al., 2011)
Intake fraction of the population for pm2.5	6.0E-06	(Doulos et al., 2008)
Intake fraction of the population for SOx	7.0E-07	(Doulos et al., 2008)
Intake fraction of the population for NOx	6.9E-08	(Doulos et al., 2008)
Total population	1955,577	(Aghemo et al., 2014)
Mortality rate of cardiovascular death per year over 100,000	78.71	(Aghemo et al., 2014)
Average breathing rate of a person (m ³ /day)	20	(Doulos et al., 2008)

Table 4
Electricity reduction for buildings for the city of Merida in Mexico.

	Reduction	Reduction (kW-h/yr)	Electrical bill (USD/ yr)	Cost Recovery (yr)	Energy saved cost (USD/ kW-h)
Self-constructed	35%	131	\$ 9.36	1.1	\$ 0.076
Commercial	40%	149.6	\$ 10.42	6.7	\$ 0.480

Table 3 illustrates the data used in this study and their respective references. These data can be obtained for other countries or cities to replicate the study. A description of the data is presented as follows:

1. The number of buildings in Merida is 489,688, the total population is 1,955,577, and the mortality rate of cardiovascular death per year over 100,000 person is 78.71 (INEGI, 2015).
2. The total average electricity consumption per year in each building in Merida is around 2200 kW-h/yr (CONUEE, 2015).
3. The fraction of the total average electricity consumption per year in each building used only by lighting is 17% (CONUEE, 2015), this is around 374 kW-h/yr.
4. The power plant emission factors in Merida are 0.655 kg/MW-h of PM_{2.5}, 20.631 kg/MW-h of SOx, and 1.633 kg/MW-h of NOx. Sanchez (2015).
5. The intake fractions of the population in Merida are 6.0E-06 for PM_{2.5}, 7.0E-07 for SOx, and 6.9E-08 NOx (Stevens et al., 2007). These values are dimensionless.

The constant data of average breathing rate of a person is 20 m³/day-person (Stevens et al., 2007).

5.1. Electricity reduction estimation for one building

To estimate the total electricity consumption reduction $\Delta E_{\text{lighting}}$ for a building in Merida, it is necessary to have the total electricity used by lighting in each building E_{building} . This amount is multiplied by the percentage of electricity consumed in lighting F_{lighting} , and by the electricity consumption reduction by the control devices C_{RI} (self-constructed 35% and commercial 40%).

$$\Delta E_{\text{lighting}} = E_{\text{building}} * F_{\text{lighting}} * C_{\text{RI}}$$

$$\Delta E_{\text{lighting}} = \left(2,200 \frac{\text{kW-h}}{\text{yr}} \right) (0.17) (0.35) = 131.0 \frac{\text{kW-hr}}{\text{yr}}$$

$$\Delta E_{\text{lighting}} = \left(2,200 \frac{\text{kW-h}}{\text{yr}} \right) (0.17) (0.40) = 149.6 \frac{\text{kW-hr}}{\text{yr}} \quad (1)$$

Table 4 illustrates the electricity that can be reduced per year in each building in Merida. Moreover, the possible savings in USD per year, and the time that a person needs to return the total cost of the control device. The self-constructed control device costs around 10

USD, savings are around 9.36 USD/yr, and the return period is around 1.1 years. The savings per kW-h is 0.076 USD, which is obtained from dividing 9.36 USD/yr by 131 kW-h/yr. Commercial control device costs around 70 USD, savings are 10.42 USD/yr, and the return period is around 6.7 years. The savings per kW-h are 0.480 USD/kW-hr, which is obtained from dividing 10.42 USD/yr by 149.6 kW-hr/yr. In the following sections, the maximum possible percentage of electricity reduction of 40% is used for the corresponding calculations of all the co-benefits from the controls strategies.

5.2. Electricity reduction estimation for all buildings in the city of Merida in Mexico

The total annual electricity consumption reduction $\Delta EE_{\text{lighting}}$ in Merida is obtained by multiplying the number of buildings $N_{\text{buildings}}$, the electricity consumed per building E_{building} , the percentage of electricity used in lighting F_{lighting} , and the electricity consumption reduction by the control devices C_{RI} , as follows:

$$\begin{aligned}\Delta EE_{\text{lighting}} &= N_{\text{buildings}} * E_{\text{building}} * F_{\text{lighting}} * C_{\text{RI}} \\ \Delta EE_{\text{lighting}} &= (489,668) * \left(2,200 \frac{\text{kW-h}}{\text{yr}}\right) (0.17)(0.4) \\ \Delta EE_{\text{lighting}} &= 73,257 \frac{\text{MW-hr}}{\text{yr}}\end{aligned}\quad (2)$$

5.3. Pollutant emissions reduction from the thermal power plant

In this study, only $\text{PM}_{2.5}$ is considered. This particulate matter is related to cardiovascular mortality of population near to the power plant. To determine emission reduction from the power plant, the equation below can be used:

$$\begin{aligned}\Delta E_{\text{PM}_{2.5}} &= \Delta EE_{\text{lighting}} * EF_{\text{PM}_{2.5}} \\ \Delta E_{\text{PM}_{2.5}} &= 1.3146 \times 10^{11} \mu\text{g/day}\end{aligned}\quad (3)$$

$$\begin{aligned}\Delta E_{\text{SO}_x} &= \Delta EE_{\text{lighting}} * EF_{\text{SO}_x} \\ \Delta E_{\text{SO}_x} &= 4.1407 \times 10^{12} \mu\text{g/day}\end{aligned}\quad (4)$$

$$\begin{aligned}\Delta E_{\text{NO}_x} &= \Delta EE_{\text{lighting}} * EF_{\text{NO}_x} \\ \Delta E_{\text{NO}_x} &= 3.2775 \times 10^{11} \mu\text{g/day}\end{aligned}\quad (5)$$

Where $\Delta E_{\text{PM}_{2.5}}$, ΔE_{SO_x} , and ΔE_{NO_x} , are the emission variations ($\mu\text{g/day}$) for $\text{PM}_{2.5}$, SO_x and NO_x , respectively. $EF_{\text{PM}_{2.5}}$ is the emission factor (kg/MW-h) for $\text{PM}_{2.5}$. EF_{SO_x} and EF_{NO_x} are emission factors (kg/MW-h) for sulfur oxide (SO_x) and nitrous oxide (NO_x), which are precursor of secondary $\text{PM}_{2.5}$ formation.

5.4. Reduction of $\text{PM}_{2.5}$ pollutant concentration in the air surrounding the thermal power plant

Intake fractions are used to know the change in exposure concentration over the population, comparing exposure assessment methods in a health benefits analysis context (Stevens et al., 2007). More detail on the methodology to obtain intake fraction can be found in relevant literature (Stevens et al., 2007; Bennett et al., 2002). The equation used is:

$$\begin{aligned}\Delta C_{\text{total,PM}_{2.5}} &= \frac{iF_{\text{PM}_{2.5}} * \Delta E_{\text{PM}_{2.5}} + iF_{\text{SO}_x} * \Delta E_{\text{SO}_x} + iF_{\text{NO}_x} * \Delta E_{\text{NO}_x}}{\text{Br} * P} \\ \Delta C_{\text{total,PM}_{2.5}} &= 0.094854 \mu\text{g/m}^3\end{aligned}\quad (6)$$

where ΔC is the change in exposure concentration of a pollutant over the population ($\mu\text{g/m}^3$); iF is the intake fraction of $\text{PM}_{2.5}$ and secondary $\text{PM}_{2.5}$ formation from SO_x and NO_x ; Br is average breathing rate of a person ($20 \text{ m}^3/\text{day-person}$); and P is number of total population of the city closer to the power plant under study.

5.5. Reduction of cardiovascular death related to $\text{PM}_{2.5}$ pollutant concentration

The thermal power plant that generates electricity produces pollution emissions, increasing the concentration of $\text{PM}_{2.5}$ in the air surrounding the environment of that power plant. This is related to mortality by cardiovascular disease in a population, particularly the population closer to a power plant. Concentration of $\text{PM}_{2.5}$ in the air must be reduced to mitigate these effects on population health. A recent study has reported that an increment of $10 \mu\text{g/m}^3$ in the concentration of $\text{PM}_{2.5}$ in the air could increase the total mortality rate of cardiovascular death per year of population exposed to those $\text{PM}_{2.5}$ emissions by 9% (0.09) (Dockery et al., 1993). Therefore, if the concentration of $\text{PM}_{2.5}$ is decreased, the total mortality rate of a population can also decrease. The following equation estimates the variation of cardiovascular deaths per year, whether the concentration of $\text{PM}_{2.5}$ is increased or decreased:

$$\begin{aligned}\Delta \text{CD} &= ((\text{CD}_{\text{rate}}/100,000 \text{ person-year}) * P * \Delta C_{\text{total,PM}_{2.5}}) * \left(\frac{0.09}{10 \mu\text{g/m}^3}\right) \\ \Delta \text{CD} &= 1.33 \text{ death/yr} \\ \Delta \text{CD} &\approx 2.00 \text{ death/yr}\end{aligned}\quad (7)$$

where ΔCD is health benefits, which, in this case, means for the change in cardiovascular deaths per year; CD_{rate} is the mortality rate of cardiovascular death per year over 100,000 (person/year), which is obtained from mortality statistics; and ΔC is the change of concentration of $\text{PM}_{2.5}$ in the air, $\mu\text{g/m}^3$.

These calculations reflect a general interpretation of what can be considered as a health co-benefit. ΔCD acquires larger significance when these implementations are scaled at a higher level, bringing further benefits to the overall population. Such measures consider the inclusion of not only houses, but large buildings and commercial facilities. Moreover, the extension of the energy management devices to air conditioning systems and electrical devices that consume power in a standby state could also bring further health benefits, significantly decreasing ΔCD .

5.6. Cost of cardiovascular death related $\text{PM}_{2.5}$ pollutant concentration

The total cost related to cardiovascular death per year $\Delta \text{CD}_{\text{total, cost}}$ is obtained by multiplying 1.2 million USD/death by the number of cardiovascular death per year ΔCD (Sanchez, 2015). The total cost is approximately 2.4 million USD/yr.

$$\begin{aligned}\Delta \text{CD}_{\text{total, cost}} &= \Delta \text{CD} * (\text{cost per death}) \\ \Delta \text{CD}_{\text{total, cost}} &= (1.33 \text{ death/yr}) * 1.2 \times 10^6 \text{ USD} \\ \Delta \text{CD}_{\text{total, cost}} &= 2.4 \times 10^6 \text{ USD/yr}\end{aligned}\quad (8)$$

6. Results and discussions

The annual electricity consumption in Merida, when lighting control devices are not used is about 1,077,313,600 kW-h/yr. However, if control devices are used in lighting the annual electricity consumption is reduced to 1,003,860,400 kW-h/yr. Therefore, energy savings are approximately 73,453,200 kW-hr/yr or 6.8% of the original energy consumption, as illustrated in Fig. 3.

Merida has three power plants, which are used to supply the total electricity demand of the city. One of these power plants uses oil fuel and generates 988,256 MW-h/yr of electricity. If control devices for lighting are used the power plant could generate 915,000 MW-h/yr of electricity, meaning 7.41% less electricity generated, as illustrated in Fig. 4.

The reduction of electricity generated by the power plant could help

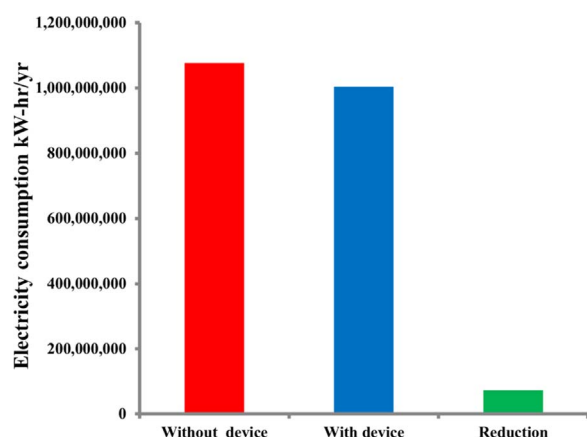


Fig. 3. Annual consumption of electricity in Mérida city.

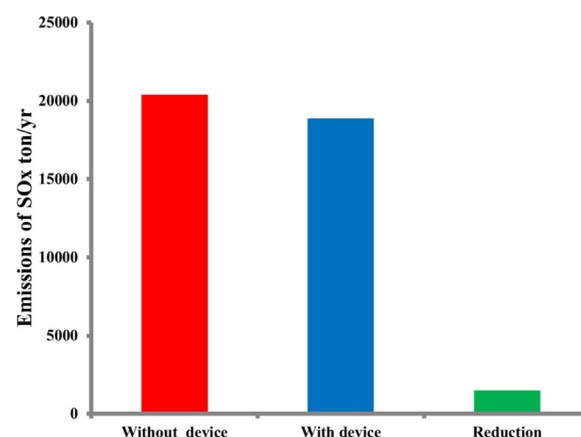


Fig. 6. Emissions of SOx (ton/yr).

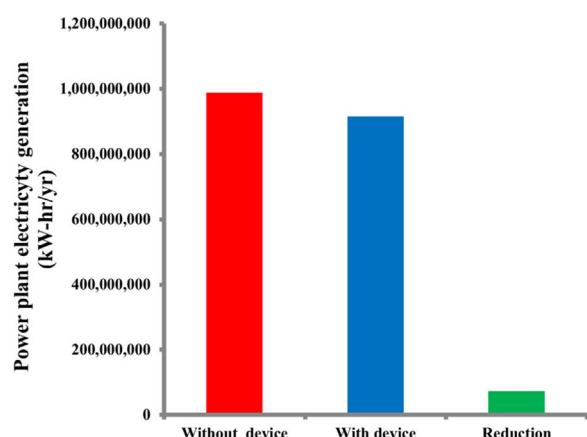


Fig. 4. Annual electricity generated by the power under study.

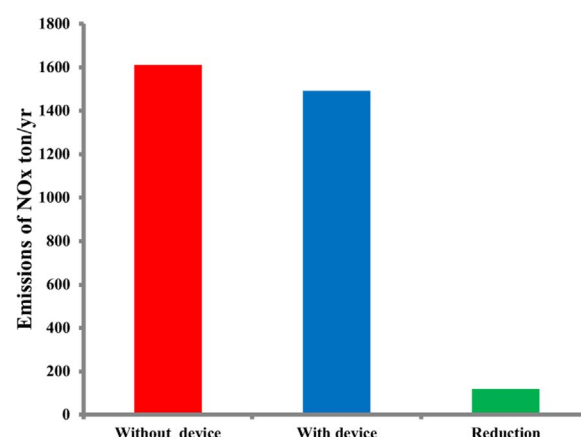


Fig. 7. Emissions of NOx (ton/yr).

to reduce pollutant emissions, which affects the population health near the power plant. The calculated pollutant emissions from the power plant for PM_{2.5}, SOx and NOx are 647.31 ton/yr, 20,388 ton/yr and 1610 ton/yr respectively. These could be decreased to 599.32 ton/yr, 18,877 ton/yr, and 1491 ton/yr of PM_{2.5}, SOx and NOx respectively. The estimations are illustrated in Fig. 5, Fig. 6 and Fig. 7.

Moreover, pollutant emission reduction could help to reduce death per year related to cardiovascular diseases, from 1579 to 1577, as illustrated in Fig. 8. The estimated avoided cost related to cardiovascular death is 2.4 MM USD. Pollutant emission reduction could help to reduce cardiovascular deaths related to those emissions. However, this study does not contemplate additional causes to these deaths, such as

nutrition and physical activity. The purpose focuses mainly on the co-benefits of the lighting control devices that could further enhance their integration in the energy market.

As previously reported in relevant literature (Kleit et al., 2012), the adoption of new technologies can only be introduced in a gradual manner, which will be a faster switch in a specific sector of the population. It has been also reported that plant size and age are two main factors that affect the adoption of new emission control technologies and further investment in those devices (Streeter, 2016). For these reasons, further studies must be carried out to report the likelihood of a considerable introduction of energy management devices in the consumer's households.

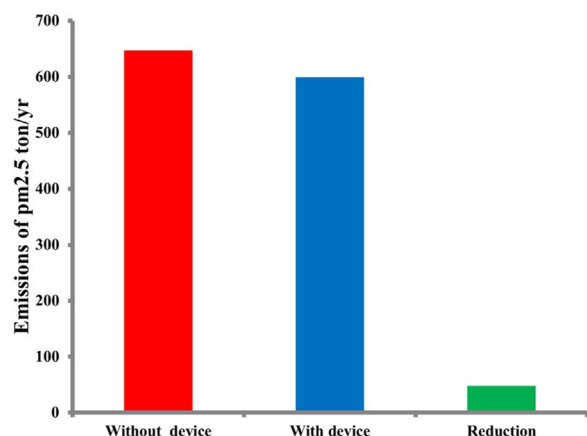


Fig. 5. Emissions of pm2.5 (ton/yr).

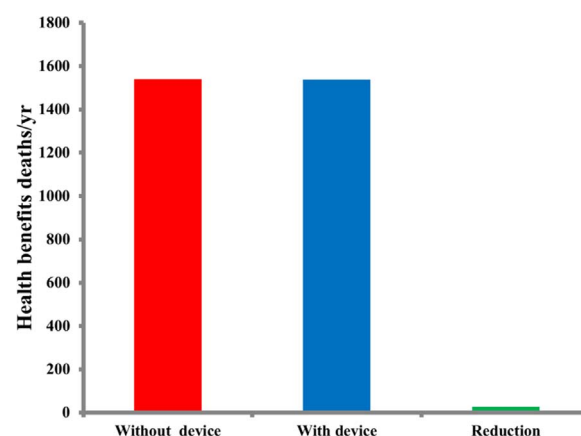


Fig. 8. Cardiovascular death per year avoided.

7. Conclusion and policy implications

The commercial control system is more expensive, since the technology is imported to Mexico; the self-constructed is cheaper and almost as efficient as the commercial device.

The high cost of commercial control devices could be an obstacle to achieve economic, environmental and health co-benefits. The results of co-benefits analysis illustrate that the advantage of implementation of control devices in Merida, which could reduce 6.8% of electricity consumption, representing 7.4% less of electricity production in a power plant in Merida. This could help to reduce the amount of PM_{2.5} pollutant emitted from the power plant, which could reduce the concentration of PM_{2.5} in the air. Finally, this could help to decrease approximately 2.0 deaths per year related to cardiovascular diseases related to PM_{2.5} pollutant, which represent 2.4 MM USD in expenses related to cardiovascular diseases.

The benefits of advanced control devices called “multiple types” for lighting in buildings could be substantial, such as energy, economic, social and environmental. However, the costs of imported commercial control devices are too expensive for people living in Mexico.

Therefore, for the implementation of advanced control devices called “multiple types” for lighting in buildings of Mexico, some recommendations are proposed for future policy decisions regarding lighting efficiency. The recommendations focus on policies concerning energy and/or regulation of toxic substances, and on support and finance programs for the use of technologies for the mitigation of pollutant emission:

- Previous research studies should be carried based on detailed cost analysis of advanced control device for lighting that does not affect its implementation.
- Economical and geographical factors have major effects of the use of the control devices for lighting. Therefore, studies must be done that consider such factors.
- Policy-makers must undertake a comprehensive and parametric study to make decisions concerning about which control devices options for lighting should be adopted in the future, and their corresponding justification.
- Policy-makers should include a comparison between the costs and benefits of lighting control devices.
- Policy-makers should include a comparison between the costs and benefits of control in energy efficiency or saving programs versus other programs.
- Further research on the likelihood of the adoption of this new technology should be carried out before a market launch. Such study must consider consumer behavior and major power plan characteristics.

This study does not contemplate the PM_{2.5} generated during the manufacturing process of the energy management devices. Its applicability into the formulation is left for future research. Furthermore, at the best knowledge of the authors, environmental tax (such as carbon tax) is inexistent in the Mexican legislation, regarding domestic or commercial use of lighting control devices. This factor is also critical for the energy policies that aim for these strategies implementation.

As a final remark, people related to job programs must incentive the generation of local companies to develop advanced control devices technologies for lighting. The main objective of this strategy is to reduce commercial prices and, consequently, aim lighting control devices to be accepted and adopted by the society more quickly. Their penetration in the market will ultimately bring energy, social, economic, environmental and health benefits.

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